Large Diameter, High Speed InGaAs Receivers for Free-Space Lasercom

H. R. Burris[1], M. S. Ferraro[2], C. I. Moore[1], P. G. Goetz[3], W. D. Waters[4], W. R. Clark[4], W. S. Rabinovich[3], L. M. Wasiczko[1], M. R. Suite[1], R. Mahon[5], J. L. Murphy[6], M. F. Stell[7], W. S. Scharpf[1], and G. C. Gilbreath[8]

[1] Naval Research Laboratory, Code 8123, 4555 Overlook Ave. SW, Washington, D.C. 20375
[2] SFA, 2200 Defense Highway, Crofton, MD. 21114
[3] Naval Research Laboratory, Code 5654, 4555 Overlook Ave. SW, Washington, D.C. 20375
[4] Optogration, Inc., 1429 Hilldale Avenue, Haverhill, MA 01832
[5] The Titan Corporation, 11955 Freedom Drive, Reston, VA 20190
[6] Naval Research Laboratory, Code 7215, 4555 Overlook Ave. SW, Washington, D.C. 20375
[7] Research Support Instruments, Inc. 4325-B Forbes Blvd., Lanham, MD. 20706
[8] Naval Research Laboratory, Code 5505, 4555 Overlook Ave. SW, Washington, D.C. 20375

Abstract

The U. S. Naval Research Laboratory (NRL) and OptoGration, Inc. have collaborated in the development and testing of large area, high speed InGaAs avalanche photodiode (APD) receivers for use in free-space lasercom systems. A 200 micron diameter InGaAs APD receiver has been tested in a free-space lasercom testbed and has demonstrated sensitivities of -42.4 dBm at 622 Mbps and -44.8 dBm at 155 Mbps. A 100 micron diameter receiver has been tested with a resulting sensitivity of -35.75 dBm at 2.4883 Gbps. These receivers are made possible due to OptoGration's capability to manufacture a large area, high speed InGaAs APD with an effective ionization ratio of < 0.2 and by matching the APD device with an appropriate transimpedance amplifier and limiting amplifier. Development and testing of the APD receivers will be described below.

Introduction

In free-space lasercom systems, atmospheric turbulence causes both small scale and large scale aberrations of the transmitted optical phase front such that the received laser spot becomes larger and moves around in the focal plane. These facts make it very difficult to couple the received laser power into a single mode fiber or onto a small, fast free-space optical detector unless a complex adaptive optics system is used.[1,2]

It is desirable to use wavelengths such as 1550 nm or 1330 nm for free-space lasercom links to take advantage of the development efforts put into components at these wavelengths by the telecom industry and to take advantage of the much higher maximum permissible exposure (MPE) limits for eye safety. However, use of these wavelengths precludes the use of silicon detectors. InGaAs detectors have very high responsivity at these wavelengths but unfortunately they typically require very small active areas to reach the bandwidths available with silicon detectors, and if using an InGaAs avalanche photodiode, they typically have an effective ionization ratio of > 0.4 such that they have much more signal dependent noise which reduces the overall detector sensitivity.[3-7]

In free-space optical communication (FSO) systems, it is usually desirable to have the sensitivity of the detector as high as possible to reduce the required laser power for a specified link margin. However, the optical receivers used for high speed optical communication systems that operate closest to the quantum limit are the PIN diode coupled to an optical fiber preamplifier and an APD. Both of these devices typically have large signal dependent noise components which must be minimized as much as possible. In addition, the fiber preamplifier has the added complexity of coupling into a single mode fiber. Although the fiber preamplifier with PIN diode can in theory have a higher sensitivity than the APD by as much as 10 dB, the sensitivity gain is offset by the difficulty and complexity of coupling into the single mode fiber.

OptoGration is now able to manufacture large diameter InGaAs APDs with ionization rate ratios that are less than half that of the incumbent InP-InGaAs APDs and are the lowest in the industry for InGaAs based APDs. This greatly reduces the excess noise factor and thus the APD shot noise so that the device has a higher sensitivity.[8-11]

Atmospheric Propagation IV, edited by Cynthia Y. Young, G. Charmaine Gilbreath,
Proc. of SPIE Vol. 6551, 65510P, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.723549

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2007**	2. REPORT TYPE
3. DATES COVERED **00-00-2007 to 00-00-2007**	
4. TITLE AND SUBTITLE **Large Diameter, High Speed InGaAs Receivers for Free-Space Lasercom**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Code 7215, Remote Sensing Division,4555 Overlook Avenue, SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**	
13. SUPPLEMENTARY NOTES	

14. ABSTRACT

The U. S. Naval Research Laboratory (NRL) and OptoGration, Inc. have collaborated in the development and testing of large area, high speed InGaAs avalanche photodiode (APD) receivers for use in free-space lasercom systems. A 200 micron diameter InGaAs APD receiver has been tested in a free-space lasercom testbed and has demonstrated sensitivities of -42.4 dBm at 622 Mbps and -44.8 dBm at 155 Mbps. A 100 micron diameter receiver has been tested with a resulting sensitivity of -35.75 dBm at 2.4883 Gbps. These receivers are made possible due to OptoGration's capability to manufacture a large area, high speed InGaAs APD with an effective ionization ratio of < 0.2 and by matching the APD device with an appropriate transimpedance amplifier and limiting amplifier. Development and testing of the APD receivers will be described below.

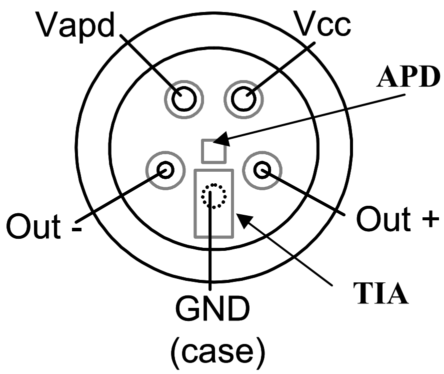
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Optical receiver construction

Several APD detectors were mounted in 5-pin TO-46 headers by OptoGration and wire-bonded to commercially available transimpedance amplifiers (TIA) from Maxim of Dallas. There have also been several devices built in house by NRL in 8-pin TO-39 headers using bare die APDs purchased from Optogration. For the 200 micron diameter detector (model OG-A-200-25 APD) we selected a MAX3658, 622 Mbps low noise TIA. The MAX3658 is a low noise (45nA input-referred noise) TIA with a 580MHz bandwidth and transimpedance gain of 18.3kΩ. For the 100 micron diameter detector (model OG-A-100-25 APD) we selected a MAX3724, 3.2 Gbps low noise TIA. The MAX3724 has an input-referred noise of 325nA at a bandwidth of 2.1GHz, and a differential transimpedance gain of 3.5kΩ. The general layout of the APDs and TIAs in the 5-pin TO-46 header along with the filter capacitor values is shown in figure 1 below. A general layout of the APDs and TIAs that were built in-house at NRL can be seen in the photos shown in figure 2.



- The receiver requires a positive APD bias.
- Vapd is routed through chip resistor (R=500Ω) to a filter capacitor (Cfilt=900pf).
- The APD sits on top of the filter capacitor in the center of the TO-46 header.
- Vcc is routed to a smaller chip capacitor (C=200pf) and then to the Vcc input.
- The pin out is as shown to the left.

Figure 1: General layout of the APD and TIA in the TO-46 header used by Optogration in the fabrication process.

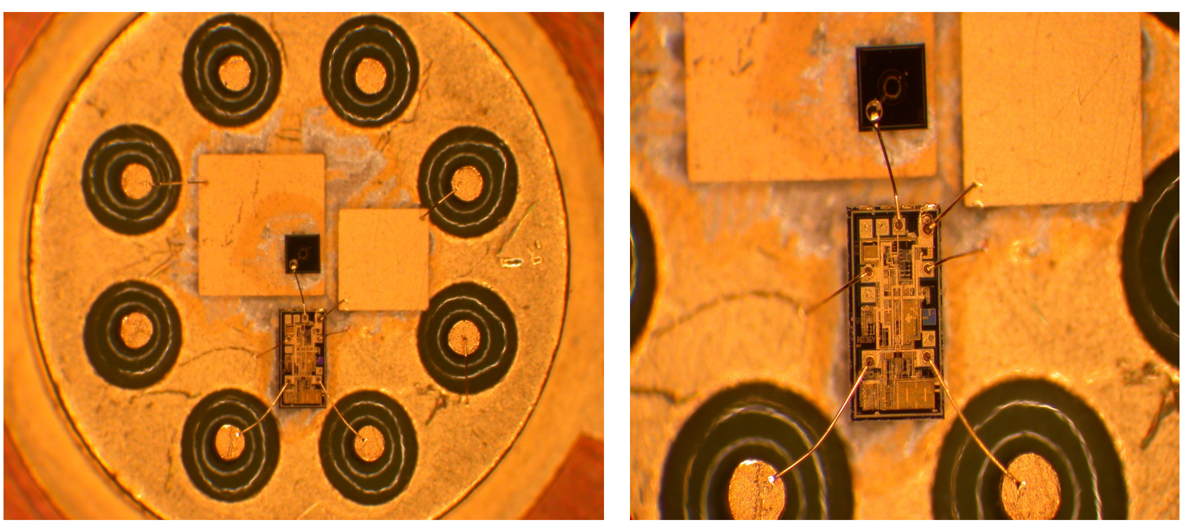


Figure 2: Photographs showing the general layout of the APD and TIA in the devices built in-house at NRL

The header caps and windows were put on the TO-46 headers by NRL. The detectors were then mounted on a small electronic amplifier board designed and built by NRL with a Maxim limiting amplifier. The MAX3747AEUB limiting amplifier was used for both receivers. The MAX3747 is a multirate, differential limiting amplifier (155Mbps to 3.2 Gbps) with > 57dB of gain. Photographs of both sides of the receiver board (in this case for a 100 micron diameter detector) are shown in figure 3. Figure 4 has photographs of the packaging of a 100 micron detector and a 200 micron detector. The packages shown in figure 4 could be made much smaller if desired. The driving requirement in this case was robustness for rapid field testing and a threaded hole over the actual detector to allow attachment of filters in Thorlabs SM series filter tubes.

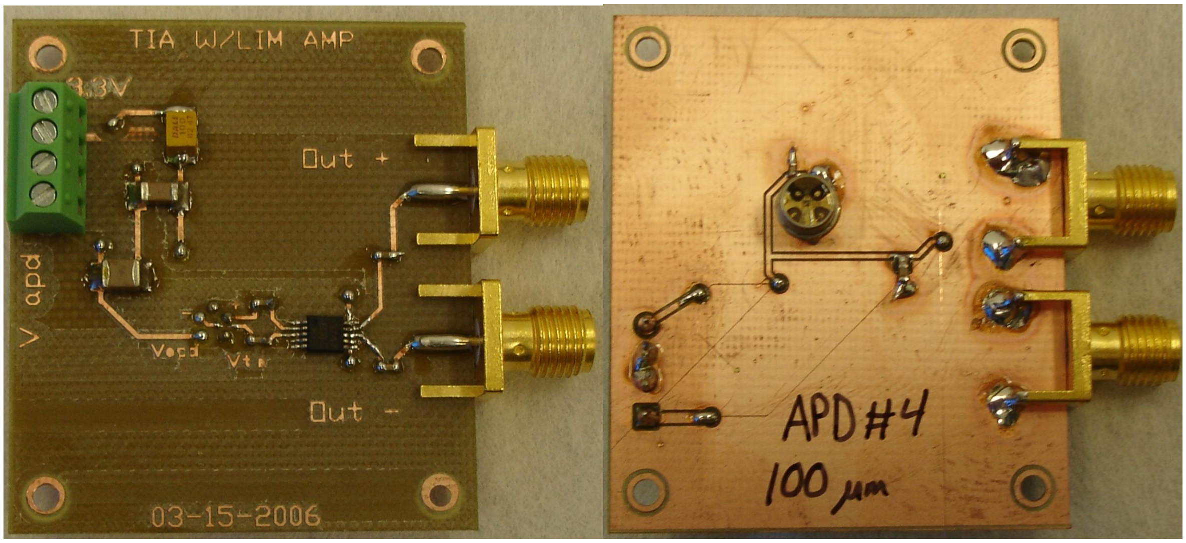


Figure 3: Photographs of the front and back views of the 100 micron diameter receiver board.

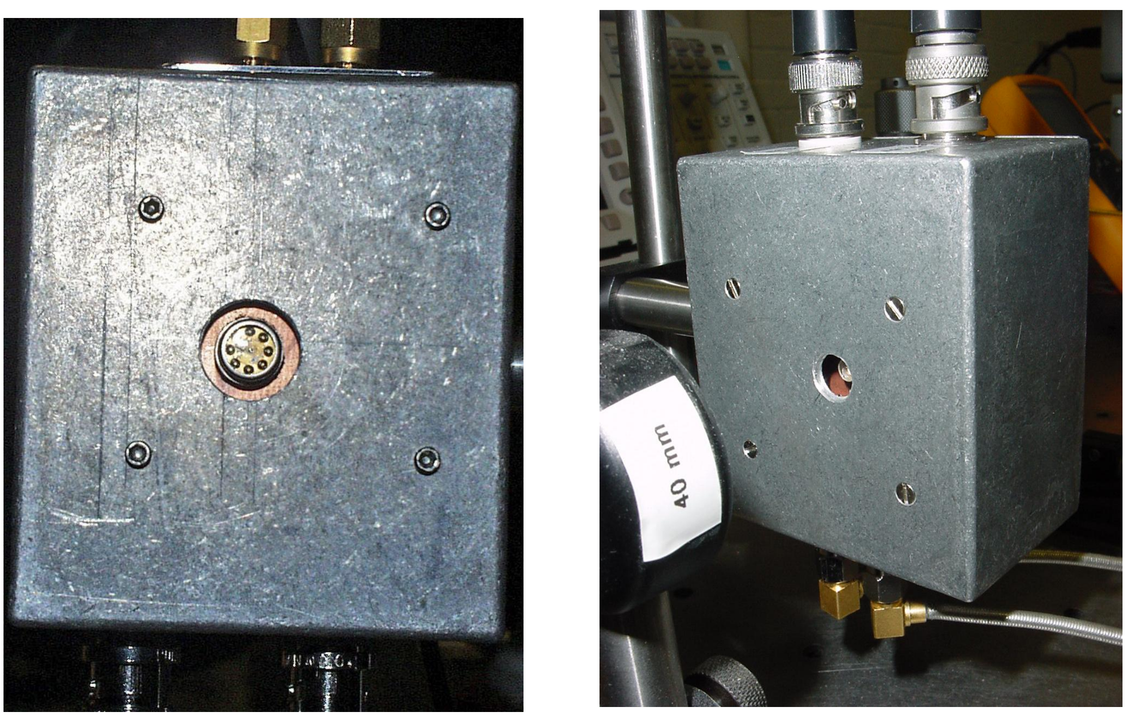


Figure 4: Photographs of 200 micron receiver (APD #5, left) and 100 micron receiver (APD #4, right).

Optical Receiver Testing

Laboratory Testbed

The InGaAs APD receivers have been tested in a laboratory test-bed for BER sensitivity and in the field in the NRL Lasercom Test Facility at the Chesapeake Bay Detachment of NRL. The BER sensitivity test-bed block diagram is shown in figure 5. The pattern generator of an Agilent 86130A 3.6Gbps Error Performance Analyzer provided a pseudo-random bit sequence (PRBS) input to a commercial OC-48 transmitter model STX-48 from Optical Communication Products (OCP). The STX-48 output is nominally 0dBm at a nominal 1550nm (1547.5nm) with an extinction ratio of 10dB (8.2dB minimum). The single mode fiber output was connected to a Kingfisher model KI 7010A-PC Optical Attenuator with an attenuation range of 2dB to 60dB. The single mode fiber output from the Kingfisher was collimated with an Optics For Research 1550nm collimator and focused onto the detector with a 40mm focal length, f/#2.2, plano-convex lens from Melles-Griot. The detector housing was mounted on an X-Y-Z translation stage to align the detector to the focal spot. The true power applied to the detectors was calibrated by using a Newport detector head, model 818-IS, with a pinhole mask of 100 microns or 200 microns (depending on which size APD detector was under test), mounted on an X-Y-Z translation stage to align to the position of maximum power in the focal spot. A later improvement of the test-bed utilized a fiber focuser from OZ Optics to replace the collimator and focusing lens. The true power on the detector was again calibrated in the same manner as above. The positive output from the differential LIA of the receiver was applied to the error detector of the Agilent 86130A, while the negative output was applied to a Tektronix model TDS5054 digital oscilloscope to monitor the waveform from the receiver. While the Agilent BER tester has a differential output from the pattern generator (both of which were used for the OC-48 transmitter), the error detector only accepts a single input. The detector under test was checked for bit error rate versus average input power at several bit rates. All of the receivers tested to date have exhibited the same sensitivities at the different bit rates within ~ 2dB.

The first two APDs that were packaged for field testing were APD #3 and APD #4 which were assembled in the TO-46 headers with the corresponding TIA by Optogration. They were then tested in the benchtop BER testbed for sensitivity. APD #3 was tested at 155Mbps, 622Mbps, and 1.0625Gbps. The corresponding sensitivities for APD #3 were -44.8dBm for a BER of 1.42×10^{-9}, -42.4dBm for a BER of 5.22×10^{-10}, and -36.2dBm for a BER of 6.43×10^{-10} respectively. Plots of the testing of APD #3 at these three bit rates are shown in figures 6 – 8. APD #4 was tested at 1.25Gbps and at 2.4883Gbps. The corresponding sensitivities for APD #4 were -36.75dBm for a BER of 1.70×10^{-9} and -35.75dBm for a BER of 1.19×10^{-9} respectively. Plots of the BER tests for APD #4 done at these two rates are shown in figures 9 and 10.

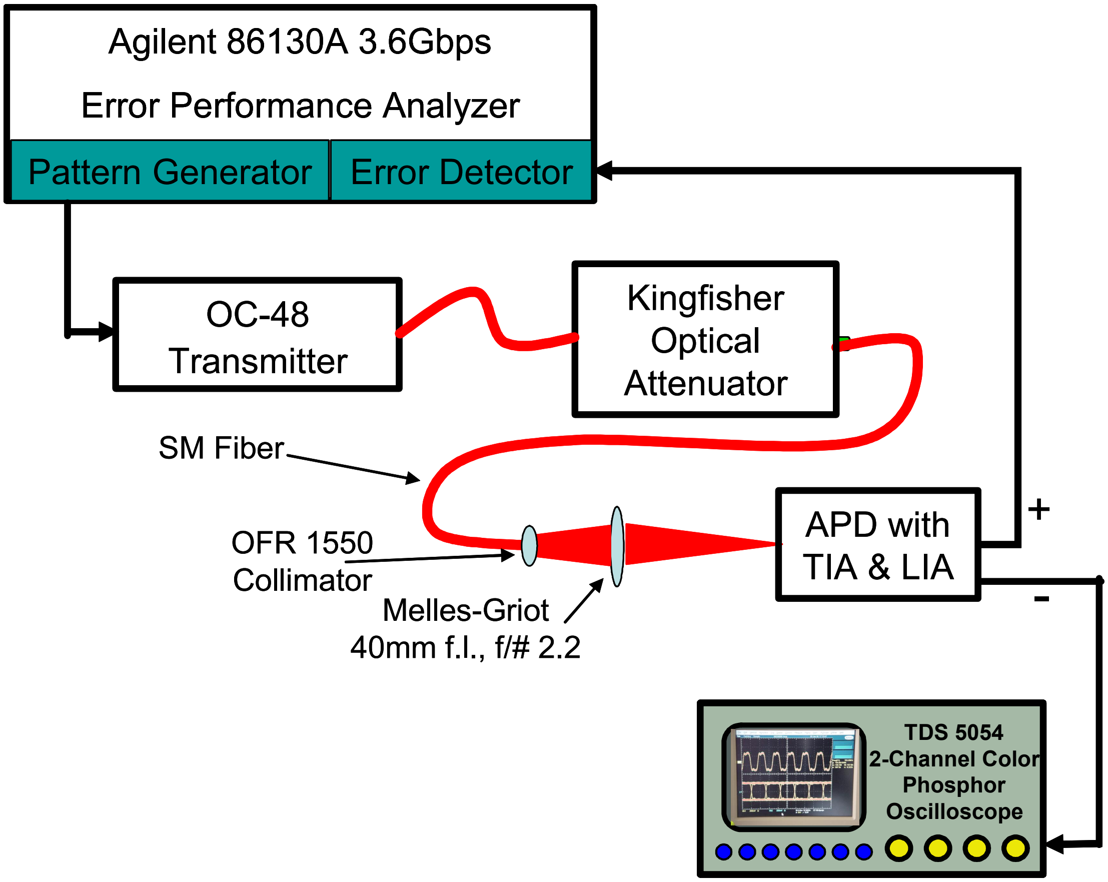


Figure 5: Block diagram of laboratory BER sensitivity test-bed

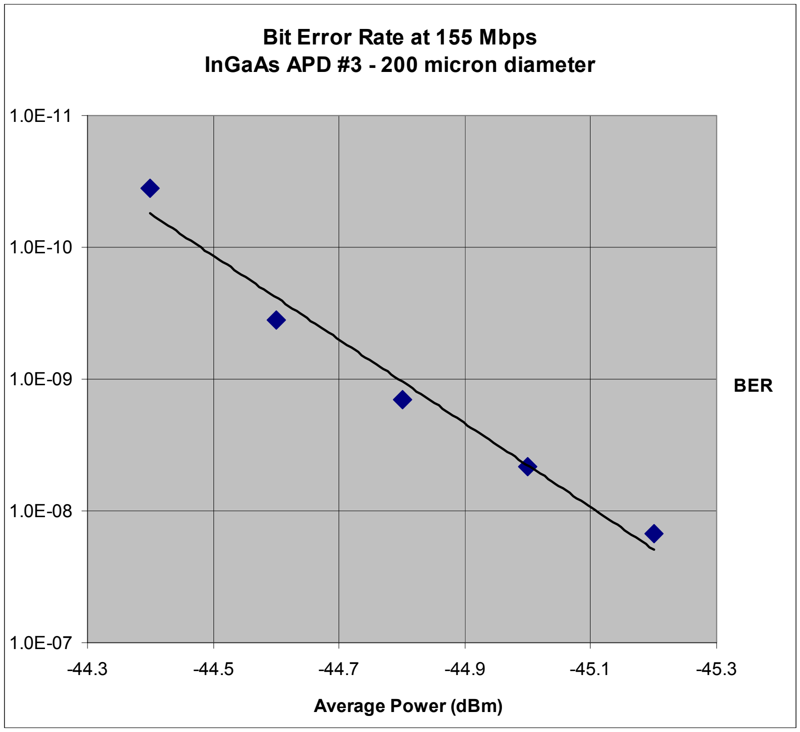


Figure 6: APD #3 BER test results at 155Mbps

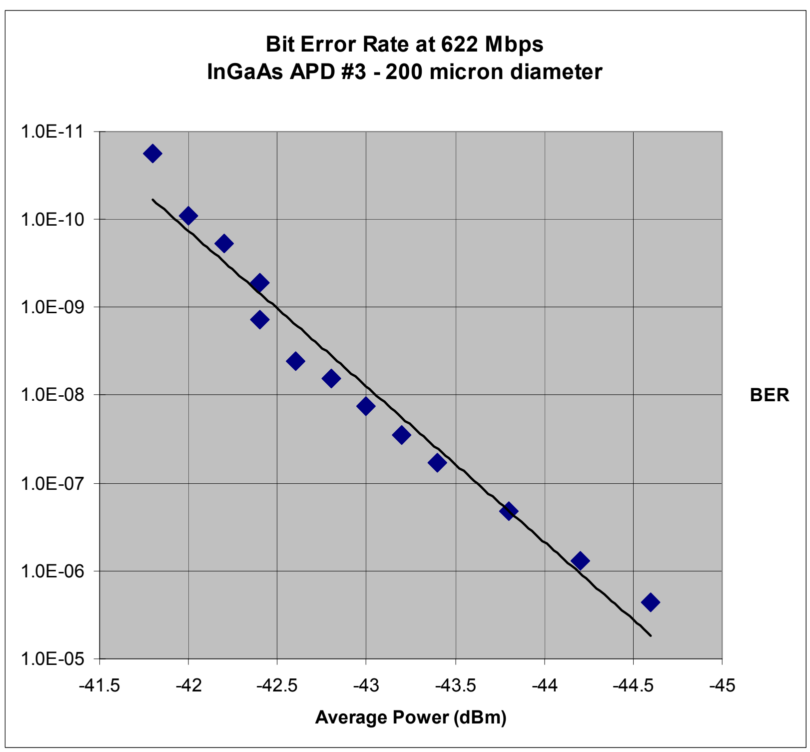


Figure 7: APD #3 BER test results at 622Mbps

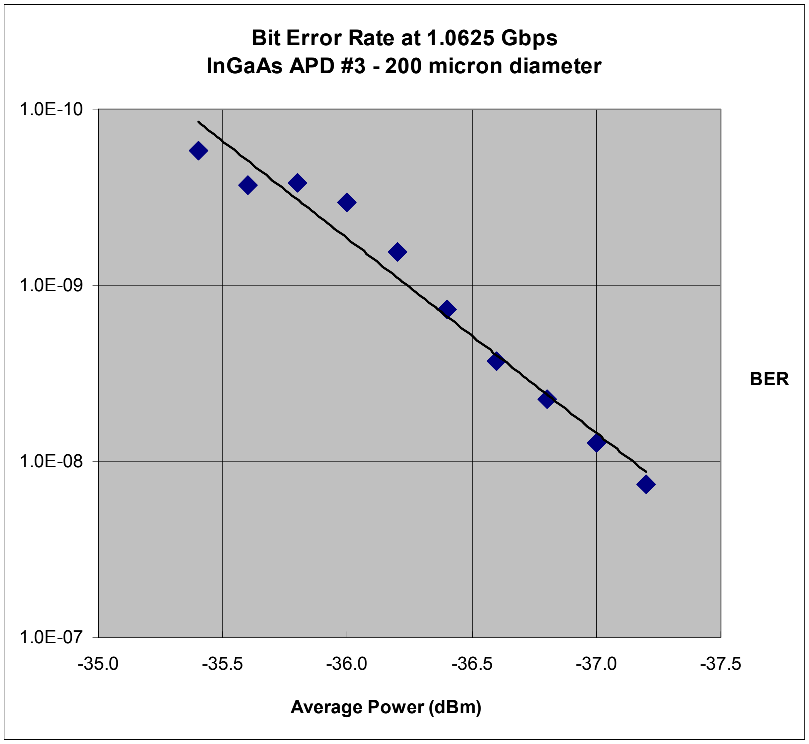


Figure 8: APD #3 BER test results at 1.0625Gbps

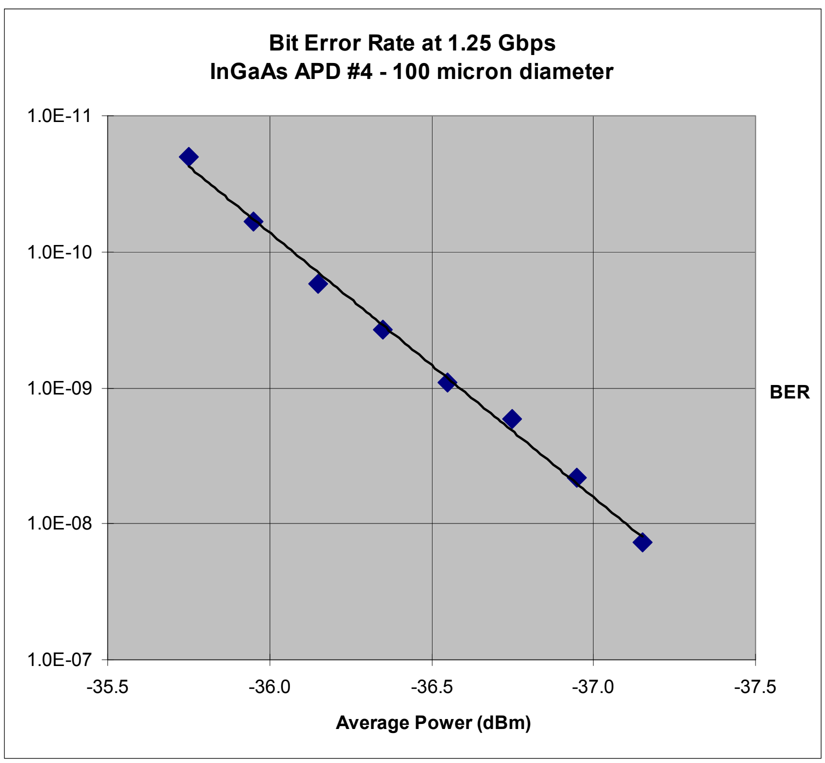


Figure 9: APD #4 BER test results at 1.25Gbps

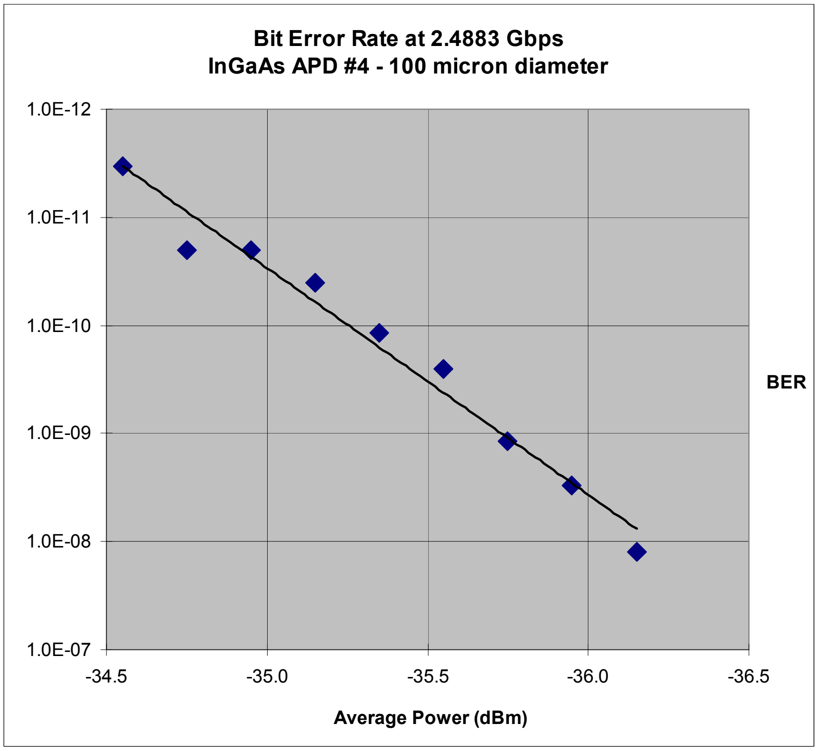


Figure 10: APD #4 BER test results at 2.4883Gbps

The BER data shown in figures 6 – 10 were obtained by connecting the output of the LIA directly to the error detector as shown in figure 5. The clock synchronization was simply done with a cable from the pattern generator to the error detector. The BER testing was done with a 2^7-1 pseudo-random bit sequence (PRBS) with a two minute average reading at each setting. Prior to testing of each receiver, the APD high voltage was optimized. The APD excess noise is a function of gain so that above a certain value of gain, sensitivity starts to drop due to the increase in excess noise.

The APDs were also tested for sensitivity with a MAX3782 Clock and Data Recovery (CDR) board connected between the receiver LIA and the error detector input. As expected, the sensitivity was reduced by approximately 3 – 4 dB due to additional errors from synch issues since the clock for the error detector was being provided by the CDR board.

It was attempted to measure the dynamic range of APD #3 receiver in the laboratory testbed; however, as was noted above, the OCP STX-48 transmitter module has an output of ~ 0dBm and the Kingfisher optical attenuator has a minimum attenuation of 2dB. An input level of -2dBm was not sufficient to saturate the receiver and 0 errors occurred during BER testing. Therefore from the laboratory tests, one can say that the dynamic range of APD #3 is at least ~ 40dB. APD #5 (figure 4) which was built in-house in the larger TO-39 header was tested for BER sensitivity and dynamic range after APD #3 was deployed for field testing. The BER sensitivities of APD #5 were ~ 1.5 to 2dB worse than APD #3 at 155Mbps and at 622Mbps. It was worse than APD #3 by ~ 3dB at 1.062Gbps. This is probably due to the increased capacitance of the larger TO header used for APD #5. The dynamic range of APD #5 was measured by inserting a 200 milliwatt EDFA into the BER sensitivity testbed and increasing power until errors started to occur at 622 Mbps. The dynamic range of APD #5 is ~ 42.5 dB.

Lasercom Test Facility

The receiver containing APD #3 (200 micron diameter with TIA optimized for 622Mbps) has been installed in the NRL Lasercom Test Facility (LCTF) receiver package on Tilghman Island for the past several months. The detector has been used extensively for bit error rate testing and for packet error rate testing in the one-way link across the Chesapeake Bay. Since mid-December, 2006, testing has been at an almost continuous 24 hours per day, 7 days per week, rate autonomously. Data collection is interrupted for ~ 1 day every 2 weeks to remove and store date before restarting. The receiver has operated flawlessly ever since installation, even through several severe storms which caused power brownouts, power surges, and power loss on Tilghman Island. While in use in the LCTF, we have not been able to saturate the receiver, even when using the full output power of the EDFA (5 watts) that is used in the 10-mile one way link across the Chesapeake Bay. However, the data collected from the three-aperture atmospheric parameter diagnostic (TAAPD)[12,13,14] shows that these detectors begin to saturate on the atmospheric turbulence induced spikes when the transmitter output power is increased to 25dBm. The saturation intensity for the 50mm TAAPD detector has been calculated to be ~ 2 x 10^{-6} W/cm^2. During BER testing on the one-way link, transmitted power has frequently been increased to power levels as high as 35dBm. At this power level, the TAAPD detectors saturate frequently but the communications receiver (APD #3) produces 0 bit errors.

In the first quarter of 2006, the NRL-CBD Lasercom test facility was upgraded to a one-way propagation path across the Chesapeake Bay. Previously, results have been reported on our round trip propagation results, where an array of 25 solid retroreflectors located on a tower on NRL-Tilghman Island, MD folded the optical link back to the CBD facility on the western side of the Chesapeake Bay [15-20]. The conversion to a one-way propagation path allows for a more accurate characterization of the path because the angle-of-arrival and C_n^2 measurements are made along one direction. Additionally, the path is on a slant, which is representative of a large deck to small deck ship-to-ship or ship-to-shore lasercom link. The transmitter located at CBD is approximately 30 m above sea level, while the receiver for the one-way link is approximately 5 meters above sea level at Tilghman Island. Figure 11 is a pictorial representation of the NRL-CBD lasercom test facility.

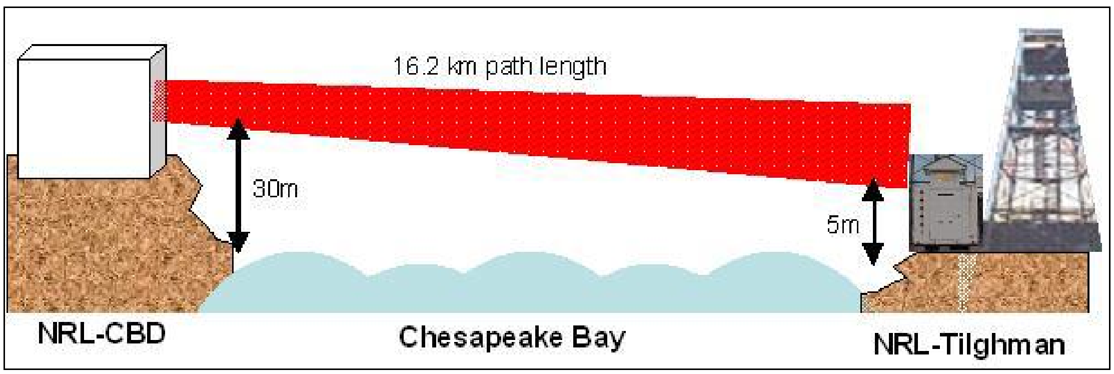


Fig. 11: NRL's Lasercom Test Facility (LCTF). The transmitter is located at NRL-CBD on the western side of the Chesapeake Bay. The receiver is located at NRL-Tilghman Island on the top of the connex box. The retro-reflector array used in round-trip testing is mounted on the tower at Tilghman approximately 15m above sea level.

The transmitter configuration implemented at the LCTF consists of the output of an EDFA amplifier launched from a single mode fiber and allowed to expand into a 4 inch achromat (f ≈ 23 cm). The fiber holder is mounted on a translation stage allowing easy adjustment of the output beam divergence. Beam steering is accomplished through the use of a 1 inch Newport Fast Steering Mirror (FSM). The system may be set up for packet testing, bit error rate testing, or video transmission over a one-way link of 16.2 kilometers or a round trip link of 32.4 kilometers. The details of the transmitter assembly can be seen in references 12 – 20.

The receiver system located at Tilghman Island consists of three subsystems that record various propagation statistics and communication metrics to assist in the characterization of free space optical communications links in the maritime environment. Figure 12 is a photograph of the receiver subsystems located on the roof of the connex container at Tilghman Island. The angle-of-arrival monitor consists of a 5 inch Orion telescope with a Spiricon 1550-M phosphor-doped Si CCD camera in the image plane of the telescope. A video tracker (DBA Systems) uses the camera video output to generate the x and y components of the image intensity centroid at a 60Hz rate. This information is digitized with a 12-bit National Instruments A/D card and used to generate the azimuthal, elevation, and radial components of the angle-of-arrival variance.[12,14,18] From these components, the path-averaged, refractive index structure function, C_n^2, may be estimated for the case of propagation at a constant elevation (approximate in this case).[18]

The lasercom receiver uses another 4 inch achromat to collect light for the communications receiver (APD #3 currently). The receiver focusing optics consist of the 4 inch achromat and a Geltec asphere (#350240) with a 10mm clear aperture located ~ 4mm from the detector active region. The combination of these two lenses results in an effective f/# of ~ 0.7 and a calculated and measured field of view > 3 milliradians. The large field of view coupled with the large active area of the detector permit operation in all turbulence conditions so far encountered without the use of closed-loop tracking and active components such as adaptive optics or fast steering mirrors. The only atmospheric conditions which prevent closing the link are those which limit the actual transmission such as heavy rain, heavy fog, or snow. The only atmospheric parameter which we correct for in this link is a slow drift in the pointing of the transmitter beam caused by thermal gradients in the air over the water. These thermal gradients change on a time scale of several minutes to hours, depending on the weather conditions.[14-17] The output of the communication receiver (APD #3) is used for BER testing, packet error rate (PER) testing or video transmission. Details of the test setups and comparisons of BER and PER testing have been presented previously in reference 20. Recent results will be presented at the SPIE DSS conference in Orlando, FL. in April, 2007.

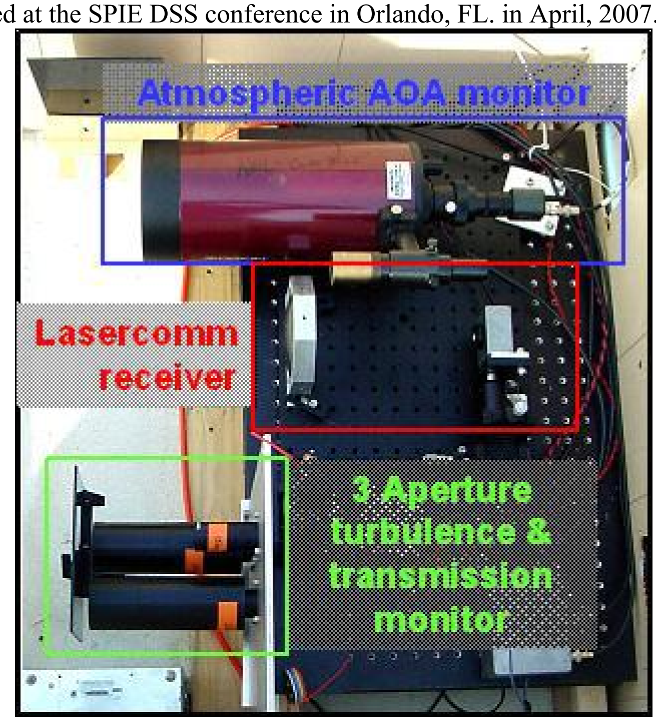


Fig. 12: The one-way across-the-bay receiver system. The system consists of an angle-of-arrival monitor (upper), a free space laser communications receiver (middle), and a three aperture atmospheric parameter diagnostic (TAAPD) (lower).

The third subsystem at Tilghman in the receiver package is the three aperture atmospheric parameter diagnostic (TAAPD). The TAAPD setup allows for the study of aperture averaging, C_n^2, and inner and outer scale. The three detectors are InGaAs Pin photodiodes with aperture stops of 15mm, 32mm, and 50mm in front of the lenses. More detailed descriptions of the atmospheric data collection systems and analysis of the data are presented elsewhere.[12,13,14]

Conclusions and future efforts

The combined efforts of Optogration, Inc., NRL Optical Sciences Division, and NRL Naval Center for Space Technology have resulted in the development of a large area, high speed, high sensitivity optical receiver for free-space lasercom applications. Laboratory and field testing have shown that these receivers have high sensitivity and large dynamic range, as well as large active areas, making them ideal for use in free-space applications.

After several months of data have been collected with APD #3 at 622Mbps (or lower when performing PER testing) at the NRL LCTF, a higher speed APD will be installed and PER testing at Gigabit Ethernet levels and BER testing up to 3.6Gbps will commence.

Future work includes development of receivers optimized for Gigabit Ethernet applications and for 100BaseT applications.

6. BIBLIOGRAPHY

1. Andrews, Larry C., and Phillips, Ronald L., Laser Beam Propagation Through Random Media, SPIE Optical Engineering Press, 1998.
2. Andrews, Larry C., Ronald L. Philips, and Cynthia Y. Hopen, Laser Beam Scintillation with Applications, SPIE Optical Engineering Press, 2001.
3. McIntyre, R. J., "Multiplication Noise in Uniform Avalanche Diodes", IEEE Transactions on Electron Devices, vol. ED-13, pp. 164-168, January 1966.
4. Olsson, N. A., "Lightwave Systems With Optical Amplifiers", Journal of Lightwave Technology, Vol. 7, No. 7, pp. 1071-1082, July 1989.
5. Alexander, Stephen B., Optical Communication Receiver Design, SPIE Optical Engineering Press, 1997.
6. Perkin-Elmer, Inc., "Avalanche Photodiodes: A User's Guide", copyright 1998 – 2000.
7. Hamamatsu Photonics, Solid State Division, "Characteristics and use of Si APD (Avalanche Photodiode)", Technical Information SD-28, Cat.No. KAPD9001E02, Aug. 2001.
8. Burris, H.R., et. al., "A Comparison of Adaptive Methods for Optimal Thresholding for Free-Space Optical Communication Receivers with Multiplicative Noise", Proceedings of SPIE, Free-Space Laser Communication and Laser Imaging II, July 2002.
9. Burris, H.R., et. al., "Adaptive Thresholding for Free-space Optical Communication Receivers with Multiplicative Noise", IEEE Aerospace Conference Proceedings, March 2002.
10. Saleh, B. E. A., Teich, M. C., Fundamentals of Photonics, John Wiley & Sons, 1991.
11. Ramaswami, R, and Sivarajan, K.N., Optical Networks: A Practical Perspective, Academic Press, 1998.
12. L.M. Wasiczko, Christopher I. Moore, Harris R. Burris, Michele Suite, Mena Stell, G. Charmaine Gilbreath, William Rabinovich, William Scharpf, "Characterization of the Marine atmosphere for free space optical communication", Proc. SPIE Int. Soc. Opt. Eng., 6215, (2006).
13. Vetelino, Frida Strömqvist, et al., Proceedings of SPIE: Atmospheric Propagation II, vol. 5793, April 2005.
14. Moore, C. I., et al. "Atmospheric Turbulence Studies of a 16 km maritime path," Proceedings of the SPIE: Atmospheric Propagation III, Vol, 5793, pg 78-88, April 2005.
15. M. J. Vilcheck, H.R. Burris, C.I. Moore, M.F. Stell, M.R. Suite, M.A. Davis, R. Mahon, E. Oh, W.J. Scharpf, W.S. Rabinovich, A.E. Reed, and G.C. Gilbreath, "Progress in high-speed communication at the NRL Chesapeake Bay lasercomm testbed", Proc. SPIE Int. Soc. Opt. Eng. 5160, 466 (2004).
16. H.R. Burris, C.I. Moore, L.A. Swingen, M.J. Vilcheck, D.A. Tulchinsky, R. Mahon, L.M. Wasiczko, M.F. Stell, M.R. Suite, M.A. Davis, S.W. Moore, W.S. Rabinovich, J.L. Murphy, E.S. Oh, G.C. Gilbreath, and W.J. Scharpf, "Latest results from the 32 km maritime lasercom link at the Naval Research Laboratory, Chesapeake Bay Lasercom Test Facility", Proc. SPIE Int. Soc. Opt. Eng., (2005).
17. C.I. Moore, et al, "Overview of NRL's maritime laser communications test facility", Proc. SPIE Int. Soc. Opt. Eng., (2005).
18. M.F. Stell, C.I. Moore, H.R. Burris, M.R. Suite, M.J. Vilcheck, M.A. Davis, R. Mahon, E. Oh, W.S. Rabinovich, G.C Gilbreath, W.J. Scharpf, and A.E. Reed, "Passive optical monitor for atmospheric turbulence and windspeed", Proc. SPIE Int. Soc. Opt. Eng., (2003).
19. M.R. Suite, H.R. Burris, C.I. Moore, M.J. Vilcheck, R. Mahon, C. Jackson, M.F. Stell, M.A. Davis, W.S. Rabinovich, W.J. Scharpf, A.E. Reed, G.C. Gilbreath, "Fast steering mirror implementation for reduction of focal-spot wander in a long-distance free-space communication link", Proc. SPIE Int. Soc. Opt. Eng., (2003).

20. M.R. Suite, H.R. Burris, C.I. Moore, M.F. Stell, L. Wasiczko, W. Freeman, W.S. Rabinovich, W.J. Scharpf, "Bit-error-rate and packet testing in free-space optical communication links over water", Proc. SPIE Int. Soc. Opt. Eng., 6215, (2006).